Concise Process Improvement Definition with Case Studies

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Abstract

Purpose

This paper examines the efficiency and objectivity of current Six Sigma practices when at the Measure/Analyse phase of the DMAIC quality improvement cycle.

Design/methodology/approach

A new method, named Process Variation Diagnostic Tool (PROVADT), demonstrates how tools from other quality disciplines can be used within the Six Sigma framework to strengthen the overall approach by means of improved objectivity and efficient selection of samples.

Findings

From a structured sample of 20 products, PROVADT was able to apply a Gage R&R and Provisional Process Capability study fulfilling the pre-requisites of the Measure and Early Analyse phases of the DMAIC quality improvement cycle. From the same sample, Shainin Multi-Vari and Isoplot studies were conducted in order to further the analysis without the need of additional samples.

Practical implications

The method was tested in three different industrial situations. In all cases PROVADT's effectiveness was shown at driving forward a quality initiative with a relatively small number of samples. Particularly in the third case, it lead to the resolution of a long standing complex quality problem without the need for active experimentation on the process.

Originality/value

This work demonstrates the need to provide industry with new statistical tools which are practical and give users efficient insight into potential causes of a process problem. PROVADT makes use of data needed by quality standards and Six Sigma initiatives to fulfil their requirements but structures data collection in a novel way to gain more information.

Keywords

Six Sigma, Design of Experiments, Quality Measurement, Process Capability, Sampling Plan

Classification

Case study

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1 Introduction

This paper outlines the sampling strategy, Process Variation Diagnostic Tool (PROVADT). PROVADT was devised to improve the objectivity during the early analysis of a Six Sigma project. It is applied when there are a large number of process factors to analyse and a relatively low volume of product to sample. This can be due to short time-frames, high sampling costs or a low production volume. Some prerequisites needed to fulfil a Six Sigma Define-Measure-Analyse-Improve-Control (DMAIC) cycle included: a Gage Repeatability and Reproducibility (R&R) study and a Process Capability study. They are used to validate the measurement system employed and to quantify the current process performance in Six Sigma's Measure and Analyse phases. These techniques are time-consuming and unless there is a measurement system issue, they will not identify the root cause of a quality problem. Reducing the time spent on a quality problem, is a major consideration in our approach.

PROVADT is able to perform Gage R&R and Provisional Process Capability studies with one set of samples. PROVADT also provides Isoplot and Shainin Multi-Vari studies. These techniques are associated with the Establish Effective Measuring System and Clue Generation phases of the Shainin System (Shainin, 1993). The Isoplot graphically visualises the measurement system variation. The Shainin Multi-Vari reduces the numbers of factors affecting Critical-to-Quality (CtQ) characteristics by eliminating the unimportant ones with data-driven information. The reduction of factors by a Multi-Vari study significantly reduces the subjectivity of the early analysis, especially when compared to common Six Sigma Analyse techniques such as Cause and Effect Matrix or Brainstorming.

This paper is structured as follows: sections 2 and 3 provide brief overviews of Six Sigma and the Shainin System respectively, giving context to the PROVADT rationale; Section 4 explains the PROVADT method, highlighting its' quality tools and establishing the parameters for the sampling procedure; Section 5 outlines three industrial case studies, where the method has been effectively applied to determine the potential root causes of process variation, whilst validating the measurement system and establishing a provisional process capability; Section 6 concludes the findings in this paper.

2 Six Sigma Approach

Motorola developed the Six Sigma methodology for quality improvement to reduce quality costs. The company's emphasis was on using advanced quality tools to achieve bottom line results. The methodology soon spread to other American-based manufacturing companies including: General Electric, Allied Signal and Texas Instruments (Aboelmaged, 2010; De Mast, 2003; Pande et al., 2000).

It is common to follow the five phase DMAIC improvement cycle during a Six Sigma project, see Error: Reference source not found (George et al., 2005; Pande et al., 2000). In the Define phase, the problem is defined and potential benefits of a quality improvement project are assessed. Then the Measure phase establishes the measurement capability and determines current performance levels. The Analyse phase uncovers root causes of defects. The Improve phase, quantifies the influences of key process variables and the process is modified to reduce defect levels. Lastly, in the Control phase, actions are taken to sustain the improved level of performance.

Figure 1 DMAIC Six Sigma Improvement Model with Tools (from (Pande et al., 2000)).

Many techniques and tools can be used during each phase of the DMAIC cycle (George et al., 2005; Pande et al., 2000). However, in the Analyse phase they often jump from an extremely subjective approach, using brainstorming and cause-and-effect matrices, to complex statistical tools to validate a causal hypothesis. This is identified as an X to Y approach to problem solving, where "experts" try to to identify causes (Xs) to explain results (Ys) (Shainin, 2012). It is a weakness in Six Sigma's "exploration" (De Mast, 2004) and the lack of "Strategic advice for efficient diagnosis" is reported by De Mast and Lokkerbol (2012). The need to develop Six Sigma's framework is also highlighted by Aboelmaged (2010). This paper introduces techniques to improve these shortcoming.

The weakness is particularly important to overcome when the cost of sampling is very high, or a low-volume of product is available to test. It has been noted that in a low volume manufacturing process, quality practitioners are increasingly leaning towards the use of subjective approaches (Julien and Holmshaw, 2012). In this situation, extremely complex Designs of Experiments (DOE) can be impractical. Using less powerful screening techniques such as Fractional Factorials, will reduce the numbers of experiments needed (as all combinations of experimental factors are not run) but at the expense of understanding higher order interaction effects (Juran and Gryna, 1988). However, the number of experiments required can still spiral out of control if there are multiple factors present. Other approaches used in the Six Sigma methodology to identify important input factors affecting CtQs, such as scatter plots, can lead to potentially erroneous results. This is due to correlations appearing as a result of coincidence, or an unidentified factor (George et al., 2005). Cause-and-effect matrices offer a method of linking input factors to outputs, but are extremely subjective. Importantly, the real root cause of a quality problem could be missed if DOE is applied based on casual hypothesis techniques, as real important factors may be eliminated subjectively.

As the remainder of this paper focuses on process improvement in manufacture, the definition of the inner-MAIC loop (MAIC referring to the core of the DMAIC strategy) will be used (De Mast et al., 2000).

3 The Shainin System Approach

Shainin strategies were developed by Dorian Shainin, beginning with the Lot Plot in 1943 (Shainin and Shainin, 1988). Over time, a body of techniques were developed and grouped into the Shainin System, (Shainin, 1993; Steiner et al., 2007). Figure 2 provides a flow chart of the general methodology and steps taken when considering a quality improvement project (Shainin, 1993).

There has been little peer review work for these methods and they have not been exposed at large to professionals because of proprietary reasons (Senapati, 2004). There is a description of Shainin techniques by Steiner et al. (2007) but the most complete descriptions are in Bhote (1991) and Bhote and Bhote (2000). These texts are heavily criticised by Hockman (1994) and Ziegel (2001) for being self-promotional and for their dismissal of classical DOE techniques. However, genuinely useful ideas are included in the Shainin approach (Steiner et al., 2007) and is shown in this paper with their introduction within the Six Sigma framework.

The Shainin System aims at finding the major, secondary and tertiary causes of variation. These inputs are known as the Red X, Pink X and Pale Pink X, which affect the output, known as the Green Y, in a problem process (Figure 2). To determine the Red X, Convergence techniques and DOE are implemented within the Shainin System algorithm, Figure 2, (Shainin, 1993; Steiner et al., 2007). Corrective action and/or Statistical Process Control (SPC) are finally implemented to control the Red X. The process of converging on a Red X is known as a Y to X approach, where differences in results (Ys) are analysed to rule out unimportant factors, narrowing down to the Red X (Shainin, 2012). The Shainin System goes through a "Generate Clue" off-line phase for eliminating variables in a process that do not have an effect on the overall variation, without disrupting the process settings. This allows DOE to be performed with the identified suspect variables using fewer experiments to narrow to the root cause, i.e. the Red X. This limits the on-line testing causing process disruption (Steiner et al., 2007).

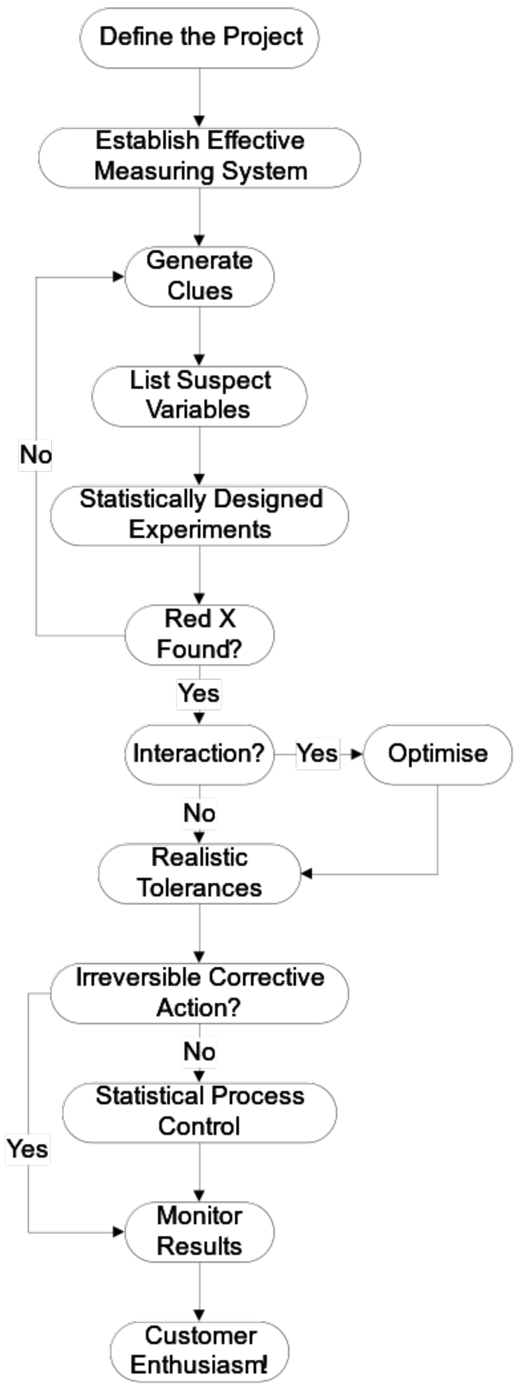

Figure 2 The Shainin System Algorithm (Shainin, 1993).

4 Process Variation Diagnostic Tool Methodology - PROVADT

4.1 Overview

PROVADT lies at the interface between the Measure and the Analyse phases of the DMAIC quality improvement cycle. It uses Tools from the clue generation phase of the Shainin System within the DMAIC framework to achieve data driven improvement. This approach introduces the following elements:

- It is structured to provide Multi-Vari, Isoplot, Gage R&R and Provisional Process Capability studies. The former technique generates a signature of variation whilst the latter are essential for the Measure and Early Analyze phases of Six Sigma.
- Gage R&R and Provisional Process Capability studies add numerical information to the graphical Multi-Vari and Isoplot analysis.
- Six Sigma and Shainin System are complemented rather than seen as competing methodologies. It introduces the philosophy of narrowing down to important factors in the Analyse phase of the DMAIC cycle.

The integration of Six Sigma and the Shainin System, and the positioning of PROVADT tools within that framework are outlined in Figure 3. This shows where the Measure and Analyse phases of Six Sigma are compatible with the "Establish Effective Measurement System" and "Generate Clues" stages of the Shainin System. It also highlights the tools PROVADT utilizes from Six Sigma and the Shainin System.

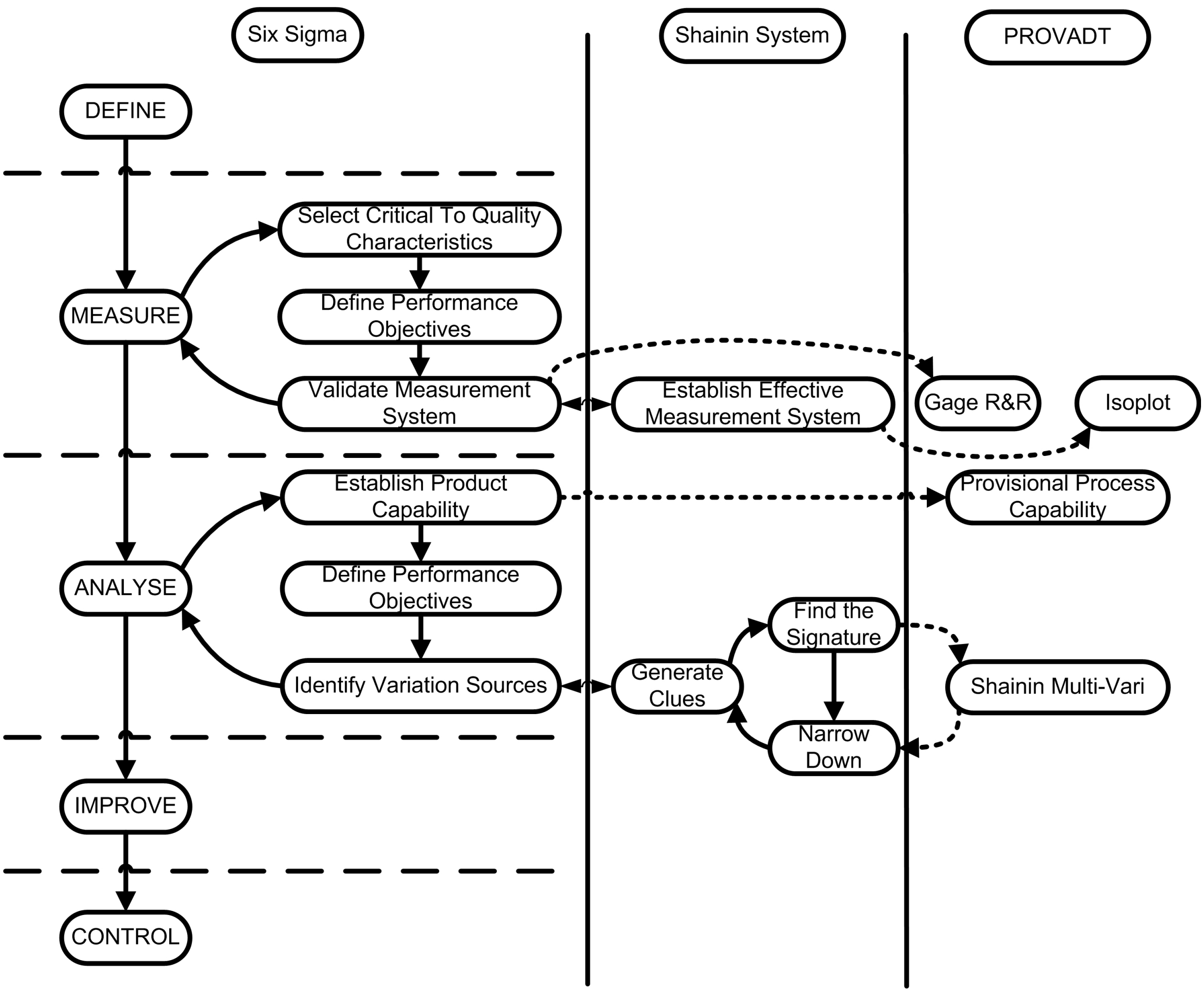

Figure 3 Outline of: Six Sigma's Measure and Analyse Phases; the Elements of the Shainin System that Fit in the Measure and Analyse; the Tools used by PROVADT and where they Fit in Six Sigma/Shainin System

4.2 Sampling Structure

The PROVADT sampling structure must be defined before implementation. This ensures sufficient data is captured to fulfil the requirements of the statistical techniques used.

A sample size (n) must be selected with a minimum of 10 units. This is the minimum number of units needed to calculate a Provisional Process Capability, also known as a Minicapability Study, (Juran and Gryna, 1988). This sample size depends also on the data collection time period (α) and the number of consecutive unit's sampled (β) from each batch or time period according to Equation (1). The minimum value for α is 5 periods and these must be spread out over a sufficient time interval for capturing at least 80% of historical variation. A sample period could be over a shift, a day, a week if collecting from a flow line. In the case of batch production, the periods could correspond to batches. For β, at least 3 consecutive samples must be used to provide the data required for the Multi-Vari (Bhote and Bhote, 2000). n is given as the product of α with β:

$$n = \alpha\beta \quad (1)$$

The CTQs on the samples should be measured repeatedly by a minimum of two appraisers. Let r_i be the number of repeats taken by an individual appraiser; then the total number of measurements taken per sample (r_{Total}) is:

$$r_{¿tal} = \sum r_i \quad (2)$$

The total number of measurements made (φ) is:

$$\varphi = n\, r_{total} \quad (3)$$

The value of φ is important for the Gage R&R calculation to be valid and must be 60 measurements or greater, which is typical for this type of study. The first n / 2 sampled units are measured by appraiser 1 first then by appraiser 2. The second half is measured by appraiser 2 first then by appraiser 1. This switching of appraiser order allows a check to see if the measurement system itself affects a product. This type of variation could be missed and seen as a measurement bias. It is also critical that appraisers 1 and 2 first measurements are in the same location, but repeat measures are made in different locations were possible. For example, measuring resistance of an electrical component can only be made in one location; measuring the diameter of a shaft can be made in different locations to check for ovality. This ensures that the check of the measurement system affect is not distorted by any product non-uniformity. The results are then analysed using Gage R&R, Isoplot, Process Capability and Multi-Vari.

4.3 Gage R&R Analysis

A Gage R&R study is a generic Six Sigma term for measurement system analysis (Hoerl, 2001) and in the manufacturing area it is the most common test for a measure's effectiveness (Pande et al., 2000). It involves repeating a measurement with different appraisers or measuring equipment to test against the repeatability and reproducibility of a gage following criteria set out in the ISO/TS 16949 reference manual, Measurement System Analysis (DaimlerChrysler et al., 2002).

Part of the PROVADT approach is to use suitable follow up techniques for identifying the important factors contributing to the root cause of a quality problem. This is important as it has been found on many occasions that Gage R&R studies are being restricted to a simple evaluation of the measurement system with the object of satisfying a third-party auditor and no action following, (Dasgupta and Murthy, 2001). It is therefore important that when PROVADT is used, to make available appropriate resources to perform follow up studies of any measurement system deemed inadequate according to ISO/TS 16949 reference manual, Measurement System Analysis (DaimlerChrysler et al., 2002).

4.4 Process Capability to Establish a Performance Measure

A process capability study statistically quantifies the variation that a process produces products with compared to the specified tolerances. It is common in the Analyse phase of Six Sigma, to establish the current process capability, which acts as a baseline for improvement projects. A complete description can be found in the ISO/TS 16949 reference manual, Statistical Process Control (DaimlerChrysler Corporation et al., 2005).

Using the first measurement taken for the n samples it is feasible to conduct a provisional process capability study. These results are not to be used to project future performance, as it is to be determined if the process is under statistical control. Given the n sampled units are collected over a time period long enough to capture 80% of historical variation, the long term capability index P is used. Let l be the lower specification limit, u the upper specification limit, σ standard deviation, $\acute{X}$ the sample mean, P_p the long term Process Capability and P_{pk} the long term within subgroup Process Capability assessing the deviation of the process mean from the process target, (George et al., 2005). This allows the following expressions of capability:

$$P_P = \frac{u-l}{6\sigma} \quad (4)$$

$$P_{pu} = \frac{u-\acute{X}}{3\sigma} \quad (5)$$

$$P_{pl} = \frac{\acute{X}-l}{3\sigma} \quad (6)$$

$$P_{pk} = min\left[P_{pu}, P_{pl}\right] \quad . \quad (7)$$

4.5 Isoplot to Graphically Display Measurement System Variation

Isoplot is a graphical technique used to home in on whether measurement variation is a result of product variation, poor repeatability, poor reproducibility or the test process itself is having an effect on the product. An industrial case study of a process improvement project for ammonia sensor in a Diesel engine, highlights how an Isoplot was applied to validate te measurement system used to test the ammonia sensors (Bovenzi et al., 2010).

Isoplots are constructed by testing *n*/2 sample units by appraiser 1 and then retesting them with appraiser 2. The second group of *n*/2 units are tested by appraiser 2 and then again by appraiser 1.

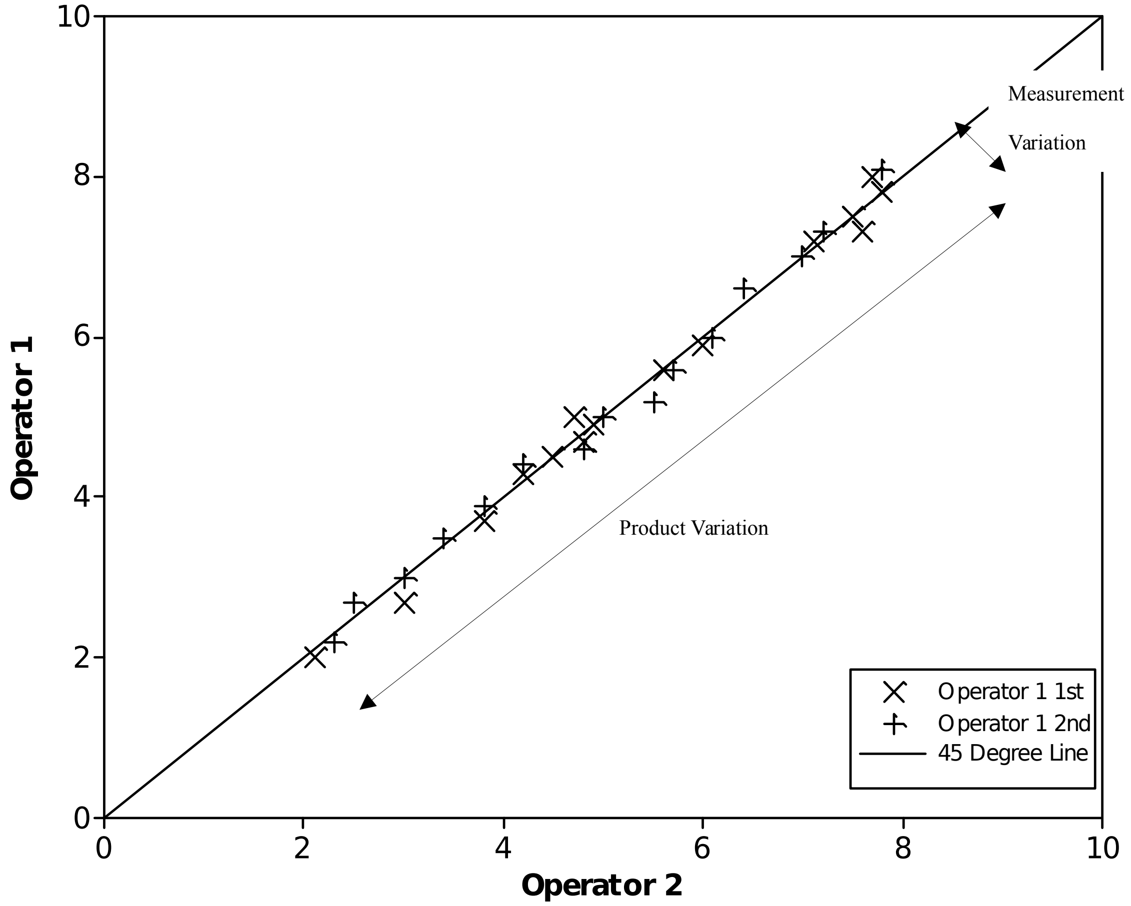

Figure 4 Example Isoplot; showing the difference between measurement and product variation.

Plotting the results on a graph, as in Figure 4Figure 3, where both axes have the same scale and for each unit the results of appraiser 1 on one axis and the results of appraiser 2 on the other , shows one of three things (Bhote, 1991), (Steiner et al., 2007): if the results are spread along a 45° line, then there is product variation; if the results are spread in a direction not on a 45° line then there is poor measurement variation or poor reproducibility; if the product variation is five times greater than measurement variation this will give the test 98% confidence in its measurement system. If the results are in two groups either side of the 45°

line then the test process has an effect on the unit. Isoplots can be developed by the same appraiser on different test equipments to show if there is a reproducibility problem between test equipments.

4.6 Shainin Multi-Vari Using the Collected Data

A Multi-Vari study as described in (Bhote, 1991), (Bhote and Bhote, 2000), (Steiner et al., 2007) and (De Mast et al., 2001) is used to find the "signature of variation", categorized as the Red X, Pink X and Pale Pink X. The Red X represents the dominant cause; the Pink X and Pale Pink X are the secondary and tertiary causes of variation. These causes belong to one of three families of process variation: within-piece, piece-to-piece and time-to-time. Specific causes are associated with each family. The Red X family should be investigated first. This is based on the Pareto principle that the vital few causes account for the majority of a quality problem. Therefore, eliminating a Red X is expected to have the largest impact on variation. A case study example of a Multi-vari study being used to identify the Red X cause of variation in the production auto-electrical alternators, is given by Jegadheeson et al.(2012).

Within-piece variation occurs within a single unit due to a poor measurement system or is the result of non-uniform product. Piece-to-piece variation occurs between consecutive units or within groups of units, due to individual processes, random variation or within-piece variation at a different level. Time-to-time variation occurs between groups of units, due to hour-to-hour, shift-to-shift or batch-to-batch changes.

In its basic form the Shainin Multi-Vari study provides a visual display of the size of the signature of variation. From this, the field of inquiry can be reduced and a suitable experiment can be performed. This is a technique that does not rely on complex statistics and it can quickly narrow down the search for the Red X without resorting to guesswork. If necessary, the visual display can be supplemented by an analysis of variance (ANOVA), utilizing the same data, to numerically estimate the size of each family of variation as described in (De Mast et al., 2001). This extra analysis does add accuracy to the categorization of the Red X but also increases complexity and time, which is only necessary when two families show similar amounts of variation.

5 Case Studies of the Practical Implementation of the PROVADT

5.1 Overview

This section outlines three case studies where PROVADT, as described in section 4, was implemented in industry. In each case, PROVADT has collected useful information to both validate the measurement system and gain an insight into the potential root causes of the respective quality problems. For all cases the parameters used are: α=5, β=4, n=20, r_{total}=3, r_1=2, r_2=1 and φ=60.

5.2 Case One: Edge Banding Trimming

5.2.1 The Quality Problem

The first case was conducted at a leading furniture manufacturer. The most critical quality issue was an Edge Banding process. This process takes Medium Density Fibreboards, which are first cut to the correct width; then the edge banding veneers are glued and applied to the freshly cut edges. The boards are then rotated so they can be cut to the correct length. The final edge banding veneers are then glued and applied to these edges.

All four edges are processed in one run.Figure 1 Output from this process is around 10,000 panels per day and had been subject of a number of quality improvement programmes over many years. At the start of the study, the company was seeing around 20% of its output being returned due to edging problems.

This case was suitable for the application of PROVADT because: it is a chronic quality problem with no obvious root cause; there are enough products to obtain a sufficient sample size (*n*); a fast solution was needed as the continuing poor yield from the process was damaging customer satisfaction and profitability.

5.2.2 PROVADT Implementation

First it was decided that the process improvement programme's focus would be the over- and under- trimming of the edging. To use PROVADT, four consecutive panels were acquired from five different time periods. The time periods were selected based on historical data in order to capture 80% of the process variation; each edge was measured three times. This means from a sample of 20 panels (4 panels × 5 time periods), each edge has a total of 60 measurements (20 panels × 3 repeated measures) taken and a total of 240 measurements taken around all four edges. Each of the four edges had the diagnostic tool applied separately as they were trimmed at different points in the machine process. Thus, each edge was numbered, as in Figure 5Figure 2, to catalogue the results separately.

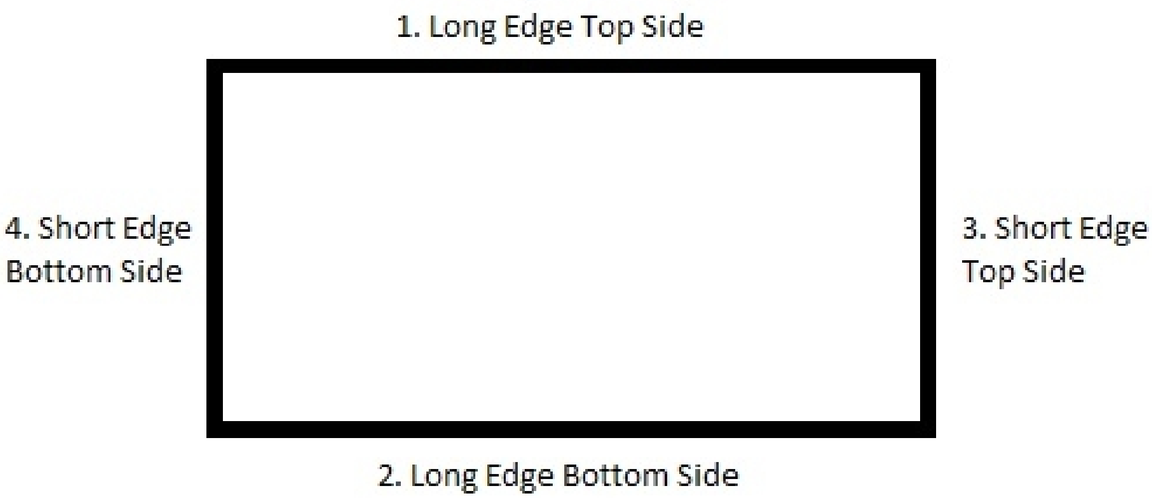

Figure 5 Panel Edge Labelling to identify the machine responsible for each edge.

A quantitative grading score for the problem was introduced, as prior to this project the product was considered only as conforming or as non-conforming. The modified labelling system, a variant of a five point Likert scale (Bhote, 1991), is shown in Table 1. This modification allows the improved expression of the process capability and helps capturing it.

Table 1 Modified labelling system implemented for the furniture manufacturer case.

2	Reject	(very under trimmed, out of specification)
1	Acceptable	(under trimmed, within specification)
0	Good	
-1	Acceptable	(over trimmed, within specification)
-2	Reject	(very over trimmed, out of specification)

5.2.3 Six Sigma Metrics to assess the Measurement System and Process Capability

The Gage R&R experiment demonstrated there was serious problem with either the measurement system or non-uniformity along the edging. Panel Edges 1, 2, 3 and 4 had scores of 78%, 80%, 53% and 20%, respectively. Three of the results are above 30% or inadequate and one result is between 10%-30% therefore marginal (DaimlerChrysler et al., 2002).

The Provisional Process Capability of the edge banding process on edges 1 and 2, which are applied at the same time in the process, are P^1_p=0.61 and P^2_p =0.66. The Provisional Process Capability of the edge banding process on edges 3 and 4, applied in the second stage of the edge banding process, are P^3_p=0.85 and P^4_p =0.98, respectively. These capability studies show a $P_p \leq 1$ in all cases; which are extremely low values, indicating the process is failing to produce sufficient products within specification. This is consistent with the high numbers of product returns experienced prior to the investigation.

5.2.4 Multi-Vari Study finding the signature of variation

A Multi-Vari was extrapolated from the PROVADT data. The Multi-Vari Studies for edges 1 and 2 are displayed in Figure 6 and Figure 7.

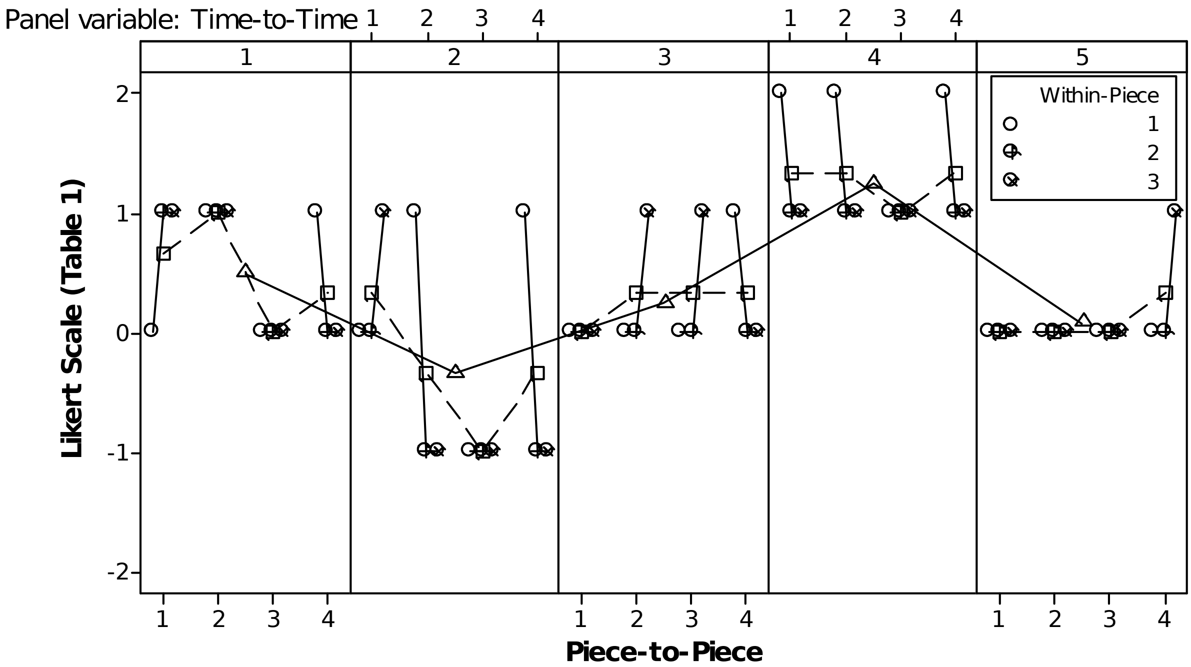

Figure 6 Shainin Multi-Vari study for Edge 1, showing Red X as within-piece and a possible Pink X Time-to-Time.

For edge 1, the largest signature of variation or Red X, is a within-piece problem. The within-piece variations are the groups of 3 circles joined by a solid line. This pattern is associated with a measurement system problem or non-uniformity along the edge.

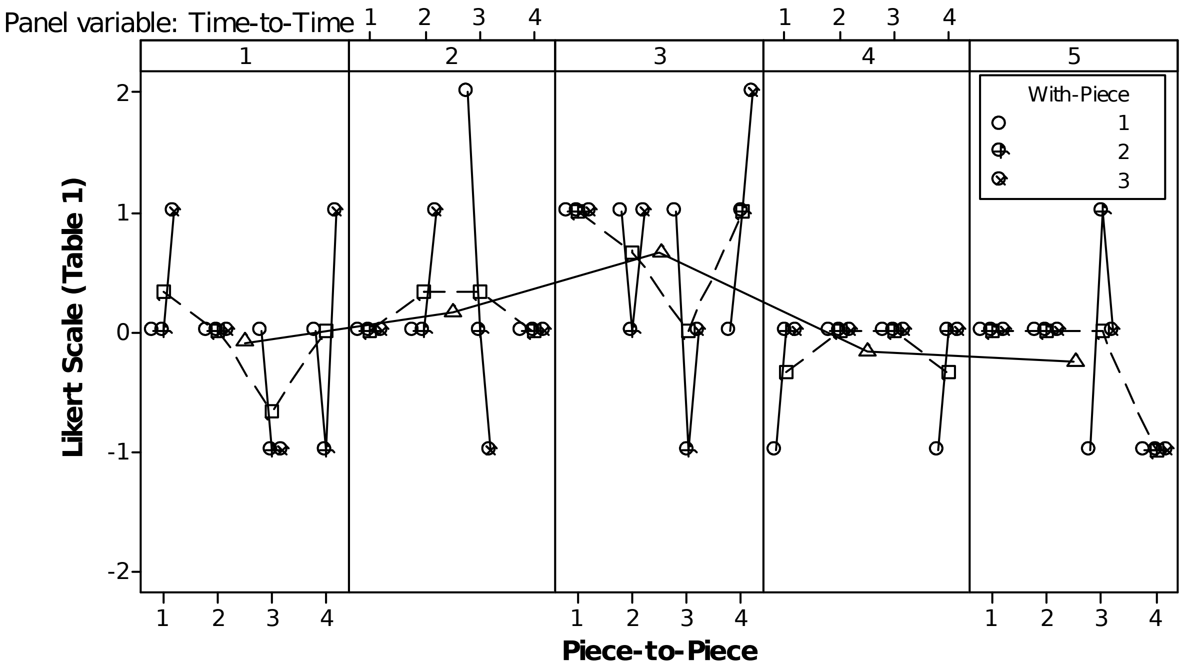

Figure 7 Shainin Multi-Vari study for Edge 2, showing Red X as within-piece.

Figure 7 highlights a within-piece Red X for edge 2. This also points towards either a measurement system issue or non-uniformity of product. The Multi-Vari Studies for the short edges 3 and 4 which are cut, glued and trimmed in the second half of the process are shown in Figure 8 and Figure 9.

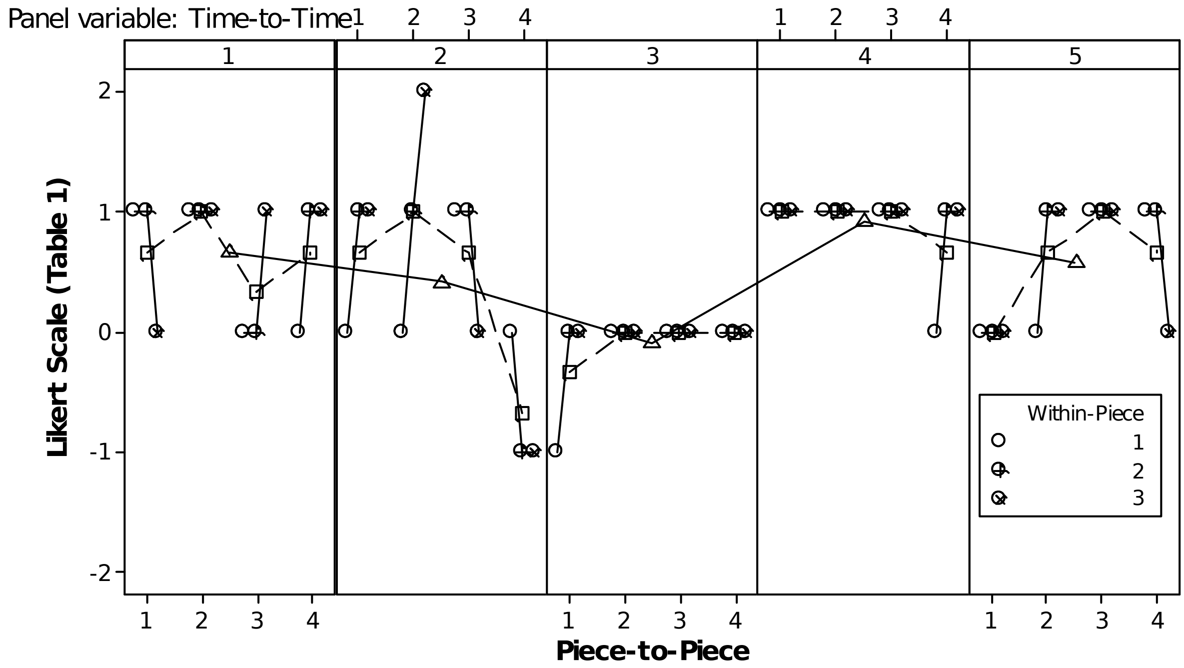

Figure 8 Shainin Multi-Vari study for Edge 3, showing Red X as within-piece.

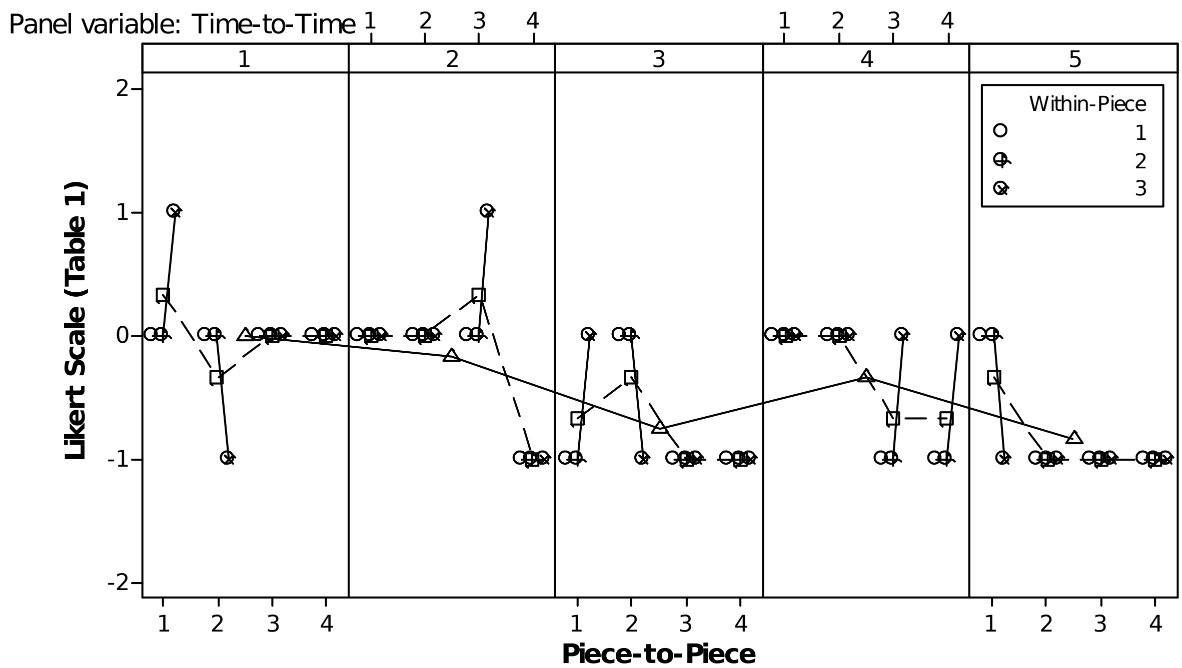

Figure 9 Shainin Multi-Vari study for Edge 4, showing Red X as within-piece and a possible Pink X Time-to-Time.

Figure 8 and Figure 9 show that the Red X for edges 3 and 4, which are machined in the second stage of the process, is a within-piece problem. The overall Multi-Vari investigation clearly showed the Red X was predominantly a within piece problem. This was consistent with the Gage R&R study which highlighted large variation across measures of the same piece. The indication, that the Red X variation is a within-piece problem, suggest that focusing on factors that influence this family of variation (measurement system, non-uniformity of product…) will have the biggest effect on improving the capability of this process.

5.2.5 Conclusions of the Edge Banding Case Study

From PROVADT the following previously suspected factors were ruled out of the investigation:

- Different size panels were affecting trimming performance; if the edging and trimming machines were affected by the size of the panels there would have to be a significant batch-to-batch change in variation.
- Settings being altered between batches; the effect of changing setting to accommodate different size panels would show up as a batch-to-batch problem.

From the application of PROVADT, further investigations were conducted focusing on full validation of the measuring system. Isoplots were used to ensure that large variation due to a poor measurement system was not masking another problem. These follow-up investigations were conducted in-house and the Quality Engineer commented that the project team had: *"driven the project further in 2 weeks than it had been in the previous 2 years"*.

5.3 Case Two: High Armature Current Difference

5.3.1 The Quality Problem

This case study was conducted at a leading manufacturer of microprocessor based electric motor control units. The control units are designed on-site in the UK. Then manufactured and tested on one of two test rigs in Poland. Finally, being retested and configured on one of two test rigs in the UK ready for packaging and distribution.

The test rigs are known as GATE (General-Purpose Automatic Test Equipment) tests and involve testing both the hardware and software of the control unit. Prior to this investigation there had been an increasing number of control units failing. Approximately 20% of all GATE tests failed, costing the company up to £800,000 per year in lost production time.

This case was suitable for the application of PROVADT because: there was an issue between test rigs, which PROVADT can be fitted to resolve; a short time-frame was available due to the financial cost of poor product yield.

5.3.2 PROVADT Implementation

Initial investigations uncovered that the number of faulty units returned to the engineers for further investigation following retesting was relatively low. The majority of fails were known as false fail's. This is where a control unit fails the GATE test but then passes when retested.

The project was defined as finding the cause of false fails on the GATE test rigs in the UK. The GATE test can produce three separate Hardware False Fails; High Armature Current Difference (ACD), Reverse Field Current Fails (RFC) and Battery Voltage Fails (BV). The common cause of fail type was ACD and was made the focus of the investigation.

To find the signature of variation, PROVADT was applied on the two UK GATE test rigs. Five test times, α=5, were selected across a day to take into account changes in shifts and breaks. At each of the five test times four units, β=4, were sampled and tested three times, r_{total}=3, twice on GATE 1 and once on GATE 2.

5.3.3 Six Sigma Metrics to assess the Measurement System and Process Capability

The Gage R&R results came out at 65.8% when measuring ACD. This result was very worrying as it was well away from the adequate guideline of 10% (DaimlerChrysler et al., 2002) and suggested that the measurement system would need the immediate focus of attention. The capability study showed that P_p=0.86, P_{pk}=0.56, indicating the process was neither capable nor centred.

5.3.4 Multi-Vari Study finding the signature of variation

The Multi-Vari investigation conducted on the GATE test rigs for ACD faults is depicted in Figure 10.

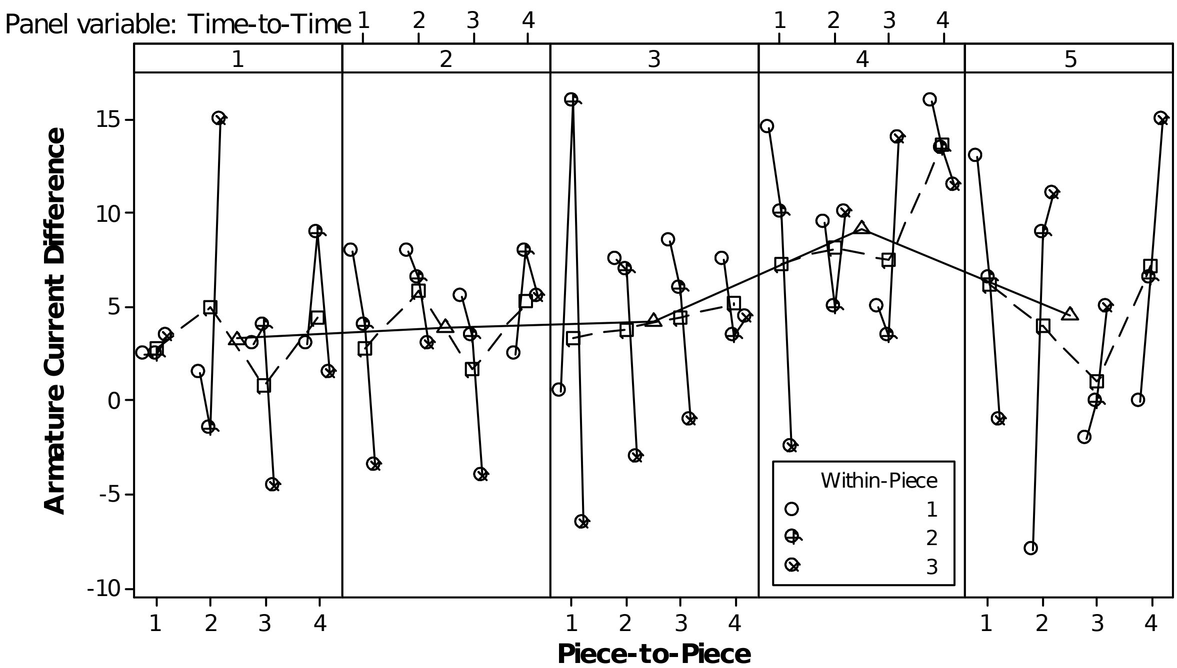

Figure 10 Shainin Multi-Vari study for ACD, showing a within-piece Red X, a time-to-time Pink X and a piece-to-piece Pale Pink X for the High Armature Current Difference case study.

The Red X in Figure 10 was clearly a within-piece problem, which is supported by the large Gage R&R value, created by large variation across repeated measurements. Figure 10 also shows that there is a lesser signature of variation or Pink X across time-to-time and a Pale Pink X piece-to-piece.

5.3.5 Conclusions to the high Armature Current Difference Study

The within-piece variation was followed-up with the Isoplot shown in Figure 11, demonstrating greater variation across GATE 1 than across GATE 2.

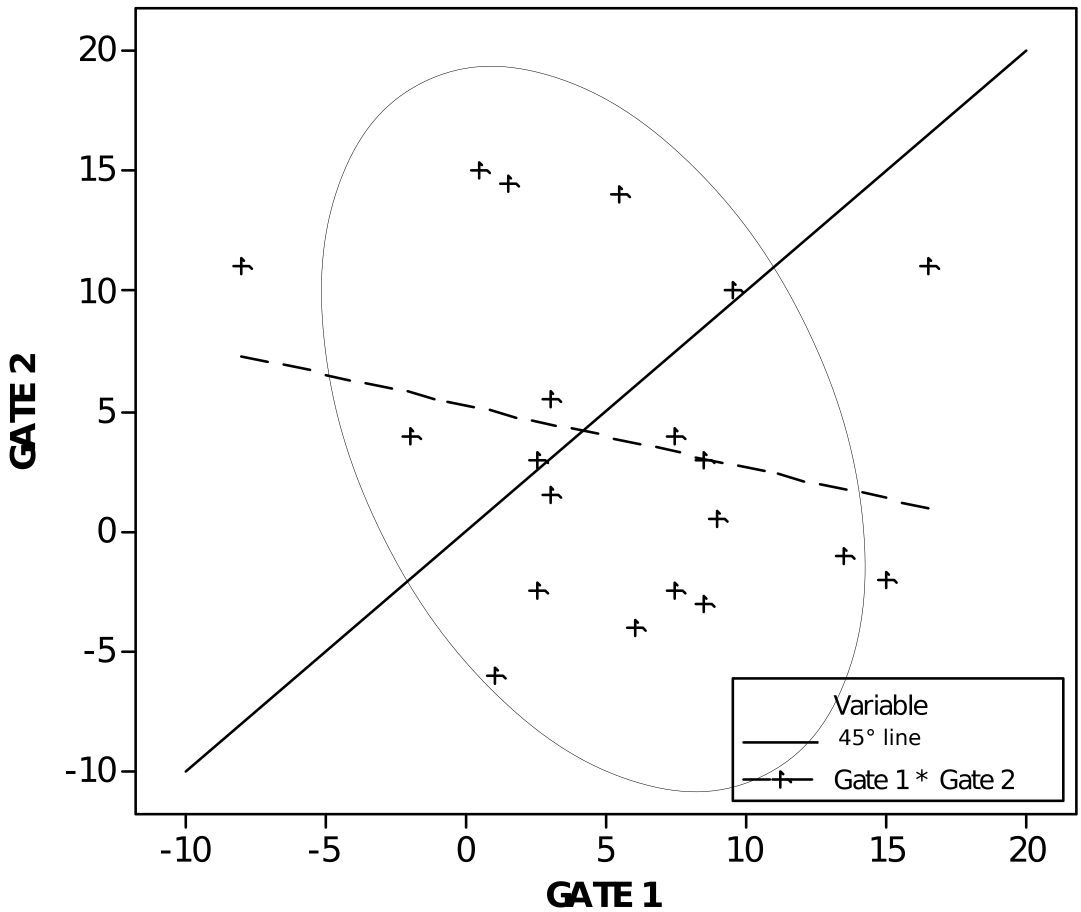

Figure 11 Isoplot between Gates 1&2 for ACD, demonstrating greater variation across GATE 1, for the High Armature Current Difference case study.

It was strongly suspected that the difference in variation across the test rigs was a result of a difference in armature current being used by the GATE test rigs. It was established that there was a significant measurement system problem that was not the result of significant product variation or of a test process affecting the result.

The time-to-time problem was followed up using a Cusum technique, (Duncan, 1974). This analysis requires additional samples to be taken. However, using PROVADT first narrows the focus of this investigation, because reduced numbers of input factors, that are potential root causes of variation, require monitoring. It highlighted a link between changes in variation seen from time-to-time with changes in supply voltage from the National Electric Grid. At 22:00 daily there was a spike in the supply voltage, which resulted in an increased response in the test results at the same time. As a result of following PROVADT on this problem, significant financial savings were made by reducing the false fail rates for ACD errors and reducing the amount of retesting needed.

5.4 Case Three: Switched on Channels

5.4.1 The Quality Problem

The third case study was conducted at a major global electronics manufacturer. The company had a long standing quality problem on a low volume process. This produced micro-channel plates for image intensifiers night sights. At the time of the improvement program, there were 200 channel plates produced per year and production was planned to increase due to growing demand. Prior to a production increase, the process needed to improve from its current yield of 25%. This extremely low yield was resulting in a financial loss.

The first step was to Define the project. From historical data it was found that 80% of faulty plates contained a Switched On Channel (SOC) fault. This is where there is no input, but occasional channels have an output. This causes spots of illumination against a dark background (brightness depends on gain of SOC).

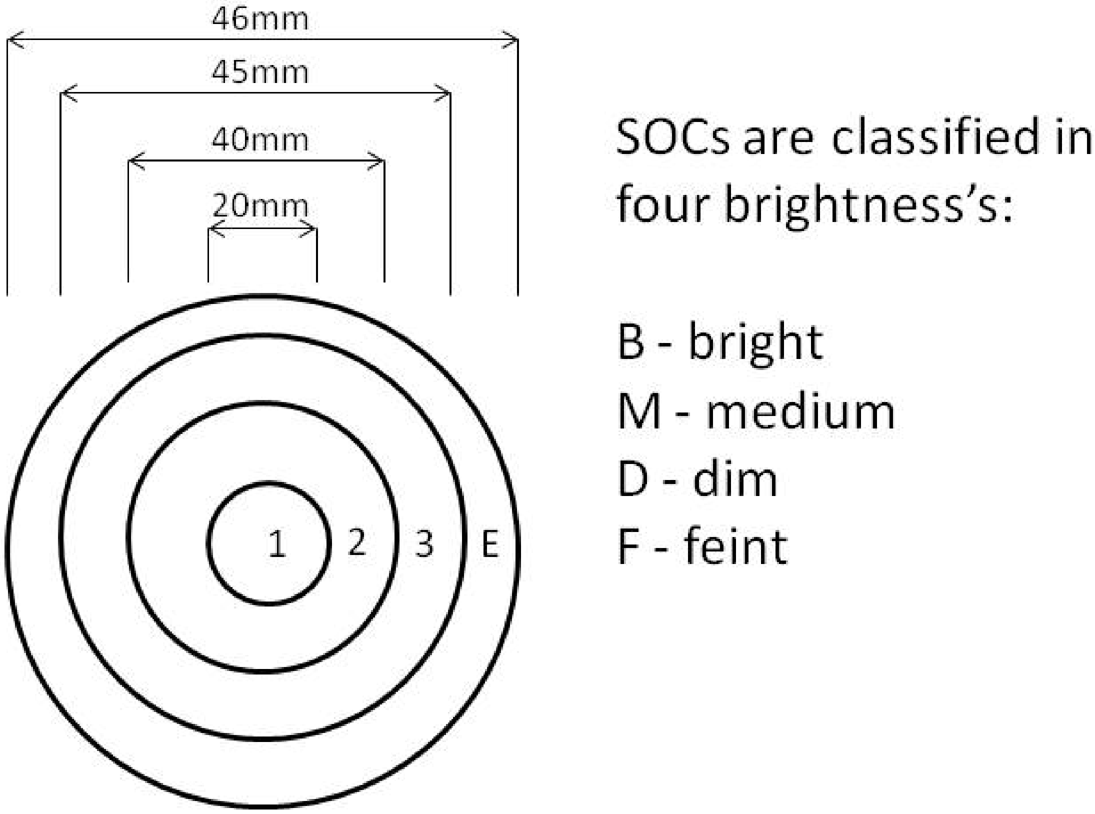

Figure 12 Grading Grid for SOC on channel plates.

Part of the project definition was to determine how to classify the SOC problem.Figure 11 Figure 12 shows how SOC are graded for customer requirements. An SOC has a zone classification of 1, 2, 3 or E based on how close to the channel plate centre it occurs. The SOC also has a brightness classification of bright, medium, dim or feint based on its visibility. A channel plate will pass inspection if it has fewer SOCs than in Table 2.

Table 2 Pass Grid for SOC.

		Brightness			
		B	M	D	F
Zone	1	0	0	1	2
	2	0	1	2	3

	3	1	2	3	4
	E	2	3	4	5

A painful process experienced in the improvement project was the categorizing of the SOCs to produce useful information. Prior to the use of PROVADT, the quality improvement project team tried to establish links between SOC location, brightness and the process. It was decided to just count the number of non-conformities on each sampled channel plate.

This case was suitable for the application of PROVADT because: it is a low volume batch production process, where PROVADT can assess variation across batches; there had been little success in previous improvement initiatives, using subjective analysis, to determine the root cause of the problem; there was a short time-frame for the necessary improvements, to allow for an effective up scaling of the process.

5.4.2 Six Sigma Metrics to assess the Measurement System and Process Capability

The Gage R&R results were 418% when measuring the number of SOC non-conformities. This result was extremely worrying, suggesting that there was a severe measurement system problem. The capability study applied a C-Chart method to accommodate the attribute measures being recorded and is shown in Figure 13.

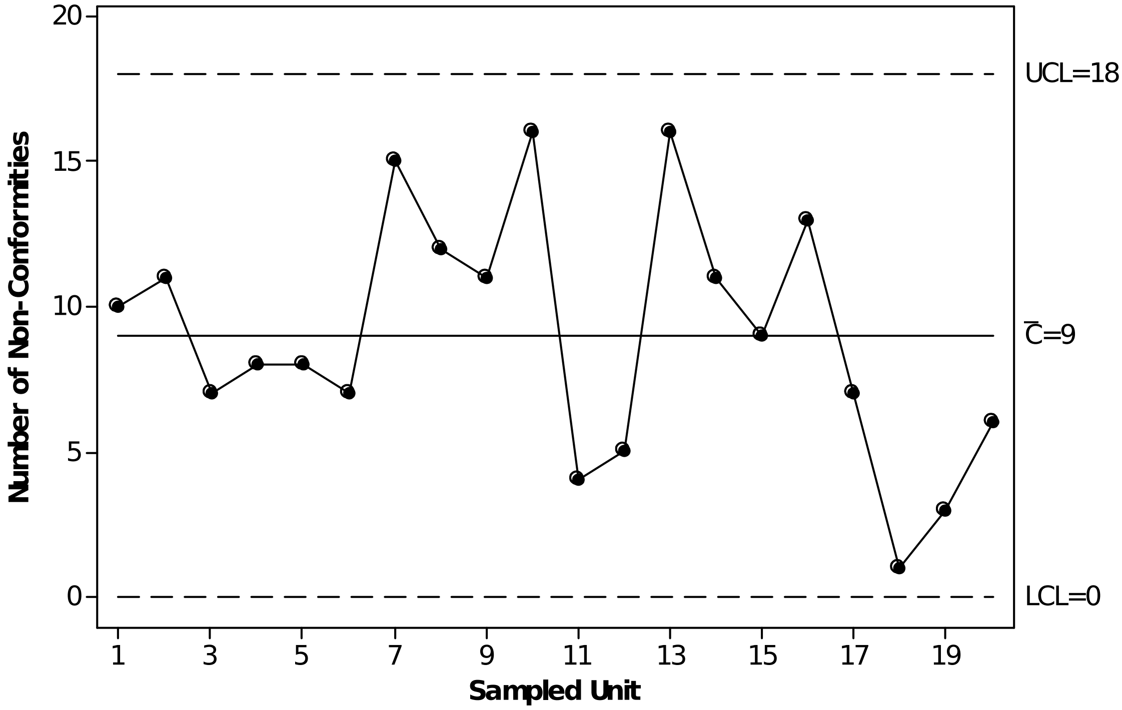

Figure 13 C-chart demonstrating the capability of the number of non-conforming SOC on channel plates.

The C-chart in Figure 13 demonstrates a high level of nonconformities with a mean number per unit of $\acute{c}$ =9. This can be classed as high or the process is not capable. If the non-conformities were all in the edge zone of the image intensifier and the SOC's were all feint, only 5 non-conformities would be needed for the unit to fail inspection. Therefore, a mean of 9 non-conformities per unit was clearly unacceptable. This led to a yield of only 25% acceptable product.

5.4.3 Multi-Vari Study finding the signature of variation

The Shainin Multi-Vari in Figure 14Figure 13 demonstrates that the least significant or Pale Pink X signature of variation appears to be time-to-time. It is highlighted by the five joined triangles. The secondary or Pink X signature of variation appears piece-to-piece, highlighted by the groups of four joined squares.

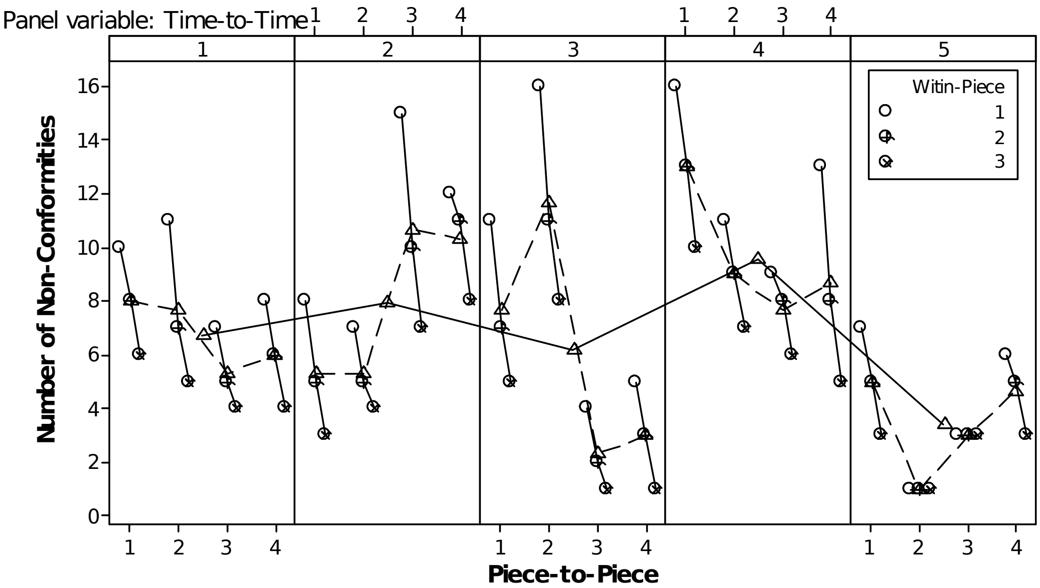

Figure 14 Shainin Multi-Vari showing a within-piece Red X, a piece-to-piece Pink X and a time-to-time Pale Pink X.

Figure 14Figure 13 most significantly shows a strong Red X within-piece signature of variation. This backs up the extremely large Gage R&R value for the SOC problem. To further explore potential causes an Isoplot was used to further understand the measurement system issue.

5.4.4 PROVADT Follow-up

The Isoplot in Figure 15 shows the difference between Test Equipment 1, which is the current test rig and test equipment 2, which is an experimental test rig.

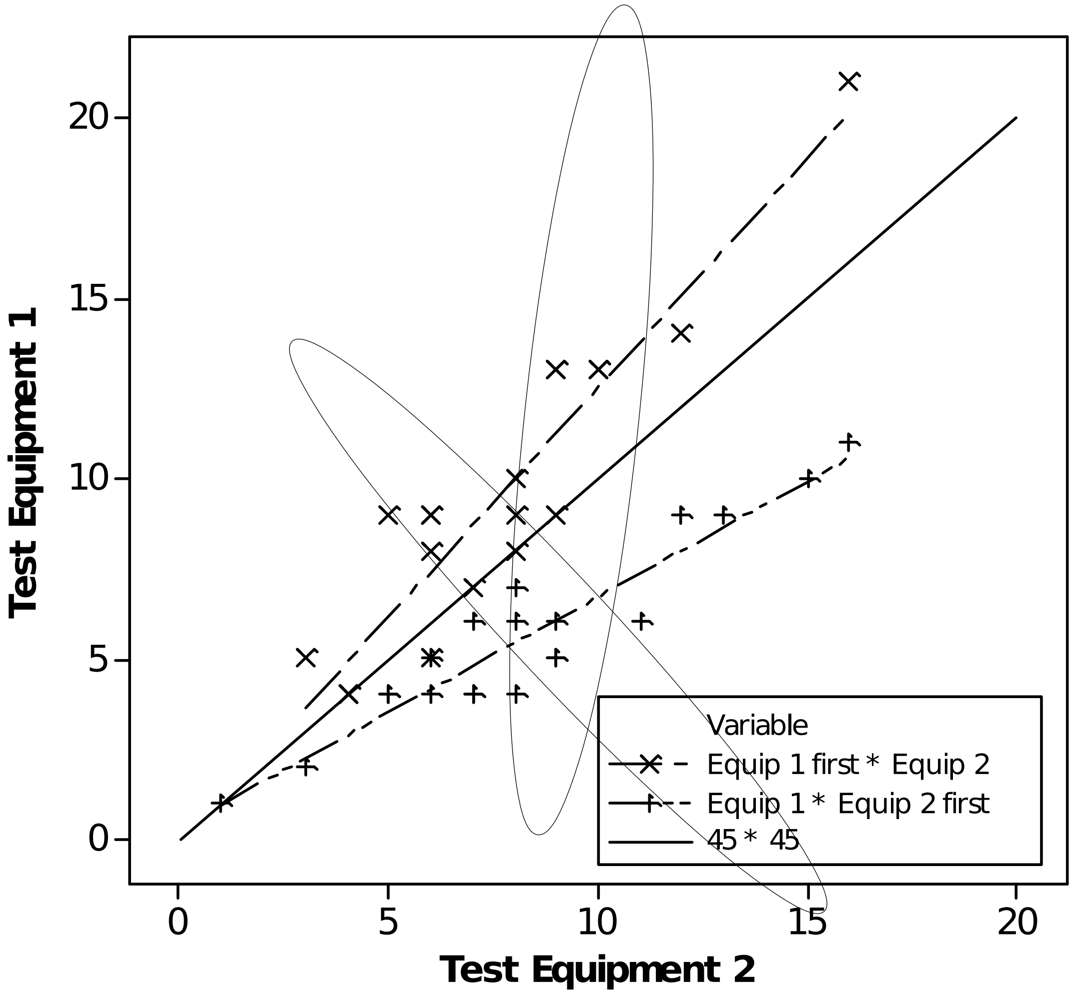

Figure 15 Isoplot for SOC measure system problem to compare variation between test equipments.

In Figure 15, two “sausages” of points either side of the 45° line are shown. These are specific to whether the channel plate was tested on equipment 1 first or equipment 2 first. Thus, this plot shows that irrespective of which equipment is used the second test always displays fewer SOC non-conformities.

5.4.5 Conclusions for the Switched on Channels Case

The Red X within-piece problem was resolved by introducing an ageing process before the channel plates are tested. This led to a significant increase in yield. This also suggests that the majority of previously disposed channel plates with SOC problems would have passed inspection had they been retested.

6 Conclusions

This paper has presented a method for increasing the efficiency and objectivity of diagnosing a process problem. PROVADT builds on the established methodology and methods of Six Sigma's DMAIC process improvement cycle. Using case study evidence, it has been shown that PROVADT can be applied to a diverse range of manufacturing processes, including: machining of furniture, testing of industrial electronics and production of optical image intensifiers.

Minimum parameters values were used in the case studies. This demonstrated, that from twenty units it was possible to fulfil the pre-requisites required to perform a Gage R&R, Provisional Process Capability and Multi-Vari Study. It was also reported how the PROVADT method on all occasions drove the improvement projects forward from the samples required to validate the measurement system.

PROVADT can be applied to any manufacturing process provided: a minimum of twenty samples can be obtained; these samples are collected in groups of at least four consecutive units, over at least five time periods; the measurement system is assumed to be non-destructive, enabling at least three repeat measurements to be taken. It must be kept in mind that PROVADT aims to capture all process variation. Therefore, it is often necessary to follow-up with further investigations as in the case studies. However, PROVADT will eliminate a significant number of unimportant factors. This will make future statistical analysis more focused and efficient; the smaller the number of suspected input factors analysed, higher order interactions can be observed with fewer experimental runs.

Development of a similar approach for the situation where destructive test equipment is used, would be of great benefit. Clearly a key aspect of the classic Gage R&R approach, and therefore also PROVADT, is that a test is repeatable. However, it is common destructive tests to be used in industry, which means a test is non-repeatable. If an approach can be formed which can validate a destructive test and start the analysis of process variation objectively, this would be an important development.

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